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13. ABSTRACT *(Maximum 200 words)*

This final report summarizes our study of the propagation and scattering characteristics of waves in geophysical media. We have conducted theoretical and experimental studies of enhanced backscattering from very rough surfaces, millimeter wave and optical experiments on scattering from random media, vector radiative transfer studies including rough surface effects, and pulse scattering from rough surfaces.

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WAVE PROPAGATION AND SCATTERING IN DENSE GEOPHYSICAL MEDIA

FINAL REPORT

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Akira Ishimaru

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I. STATEMENT OF THE PROBLEMS STUDIED

For the past years, we have been conducting extensive basic research on millimeter and optical wave propagation and scattering in geophysical media. These media include hydrometeors, fog, hail, smoke, dust, turbulence, ice, snow, and vegetation which often severely affect communication and target detection in the atmosphere. We have been successful in making substantial contributions in this field. On the basis of our extensive background and capabilities, we proposed to conduct theoretical and experimental studies on wave characteristics in such random media. We conducted carefully controlled millimeter, microwave, and optical experiments so that the experimental results could be compared with theoretical predictions. We also proposed to conduct theoretical and numerical studies in conjunction with experimental studies. The studies included coherent and incoherent fields, beam waves, pulse waves, backscattering enhancement, depolarization, angular and range resolutions, vector radiative transfer, and target identification. This basic information should be useful in clarifying the wave characteristics in the actual geophysical environments and their effects on communications, radars, lidars, polarimetric radars, and target resolution and identification.

II. SUMMARY OF MOST IMPORTANT RESULTS

A. Enhanced Backscattering from Very Rough Surfaces

When the rms height of a rough surface is of the order of a wavelength and the correlation distance is such that the rms slope is close to unity, the surface is called a "very rough surface" and at present this is outside the range of applicability of conventional theories. However, in this range of parameters, enhanced backscattering takes place, and this has attracted considerable attention among workers in geophysics and surface optics. We have conducted extensive studies on this problem -- theoretically, numerically, and experimentally. Theoretical studies are made using the first- and second-order Kirchhoff approximations with shadowing corrections. The theory agrees with numerical simulations if the surface is a perfect conductor or very lossy and the incident wave is s-polarized. However, for p-polarization, the surface wave effects may be contributing to some differences between theory and numerical simulation. Also noted is the dependence of numerical simulations on the surface integration length. These differences will be studied in the near future. We have also conducted millimeter wave experiments on very rough surface scattering, and the experimental results are in close agreement with the numerical simulations if the spot size of the experimental beam is used as the integration length of the surface for numerical simulations.

Paper No. (2) in the list of our publications in Section III discusses the advantages of the phase perturbation method over other conventional perturbation and Kirchhoff approximations. The phase perturbation method was previously developed by Winebrenner and Ishimaru. Papers (12), (13), (15), and (16) give the complete development of the analytical theory of very rough surface scattering and backscattering enhancement based on the first- and second-order Kirchhoff approximations with shadowing corrections. They are compared with numerical simulations (12) and with millimeter wave experiments (16).

The above studies are limited to one-dimensional rough surfaces. We are now extending the above results to two-dimensional surfaces. A machine capable of cutting surfaces according to a prescribed profile has been obtained, and two-dimensional rough surfaces are being prepared at present. Experiments on these surfaces should give us very valuable surface scattering data which include all polarization effects from surfaces of

known statistics. Theoretical studies on two-dimensional surfaces are also under way, and we expect to be able to compare theoretical results with experiments. Numerical simulations of two-dimensional rough surface scattering have also been attempted even though computer storage may limit the range of its applicability. The results of this study on two-dimensional rough surfaces should be applicable to realistic practical problems of terrain and geophysical environment, and the experimental data should provide valuable information to aid in construction of useful theoretical scattering models.

B. Mueller Matrix for a Random Medium with Random Surfaces

Volume and surface scattering from random media are important in several applications in geophysical remote sensing, communications, and target identification. We have developed computer codes for combined volume scattering and rough surface scattering. Complete vector radiative transfer equations are solved using the discrete ordinate method, and the results are combined with Kirchhoff approximations for rough surfaces. Detailed computer codes have been developed for calculating the Mueller matrix and the polarization signature of the scattered wave from a slab of random scatterers with the slab surface consisting of rough surfaces. Two cases are considered. One is rough surfaces with moderate rms height for which the series representation of the Kirchhoff solution has been used. The other is very rough surfaces where the geometric optical approximation of Kirchhoff solutions has been used. Although these codes are now available, it is necessary to relate the parameters in the codes to the actual geophysical parameters for practical applications. The development of these codes is detailed in Papers (21) and (22). Applications of these codes to optical scattering by leaves are discussed in (10), (11), and (19). Calculated transmission, reflection, and degree of polarization are compared with experimental data showing good agreement.

C. Radiative Transfer, Beam Wave, Imaging and Pulse Scattering

Our previous work on backscattering enhancement from discrete scatterers has been extended to include moderate and large particles sizes (3) and (6). For particles with large size, the radiative transfer equation becomes increasingly difficult to solve numerically because of the sharp angular spectrum of the phase function. The second-order theory is found to be useful in this case (5). A general review of the enhanced backscattering is given in (8) and the application to optical diffusion in tissue is discussed in (7).

Beam wave solution of the radiative transfer equation is difficult because of the large number of spatial spectra. The general formulation and numerical codes for this problem are given in (1). Imaging through a random medium in terms of the modulation transfer function is given in (4) and the experimental work is discussed in (9). A preliminary study on pulse scattering from rough surfaces is given in (16). Some work on the use of artificial neural networks for particle sizing and determination of rough surface parameters is discussed in (14) and (20). A general review of wave propagation and scattering in random media and rough surfaces is given in (17) and a review of backscattering enhancement including turbulence, particles, and rough surfaces is given in (18).

D. Optical Scattering Experiment

During the past several years, we have constructed a carefully controlled optical scattering measurement system. We had vertical and horizontal intensity measurements which resulted in the critical measurement of the coherent intensity in a dense medium and the backscattering enhancement. Recently, we extended our system to the measurement of the complete Stokes vector and the Mueller matrix. The details of the system are described

in the M.S. Thesis "Optical Mueller Matrix Measurement System" by P.K. Phu, our Ph.D. student, University of Washington, 1989. The incident polarizations are Vertical, Horizontal, 45°, and LHC, and the detector can measure Vertical, Horizontal, 45°, 135°, LHC, and RHC. As an example, we show the comparison of the experimental data with the radiative transfer solution, including rough surface effects, for a laurel leaf (11). We also show the measured 16 elements of the Mueller matrix as functions of the scattering angle (transmission $-90° < \theta < 90°$ and backscattering $90° < \theta < 270°$). Currently, we are modifying our system to obtain complete bistatic characteristics in θ (elevation) and ϕ (azimuth) directions with full polarimetric capability.

E. Millimeter Wave Experiment

We have constructed a millimeter wave system (75-100 GHz) to measure the rough surface scattering. The advantage of using millimeter waves is that we can construct the actual rough surface with given statistics. We have also constructed a one-dimensional rough surface with Gaussian spectrum and power law spectrum for $\sigma = \ell$ - 3 mm for use at 100 GHz (λ = 3 mm). These experiments have been used to study the enhanced backscattering from very rough surfaces and the results show good agreement with numerical Monte Carlo simulations (23). These experiments are now extended to two-dimensional rough surfaces, and it is expected that complete polarization information will be obtained.

III. LIST OF MANUSCRIPTS SUBMITTED OR PUBLISHED UNDER ARO SPONSORSHIP DURING THIS PERIOD

Books

A. Ishimaru, *Electromagnetic Wave Propagation, Radiation, and Scattering*, 637 pages. New Jersey: Prentice Hall, 1991.

Journal Articles

1. H.-W. Chang and A. Ishimaru, "Beam wave propagation and scattering in random media based on the radiative transfer theory," *Journal of Wave-Material Interaction*, 2:1, pp. 41-69, January 1987.

2. S. L. Broschat, L. Tsang, A. Ishimaru, and E. I. Thorsos, "A numerical comparison of the phase perturbation technique with the classical field perturbation and Kirchhoff approximations for random rough surface scattering," *Journal of Electromagnetic Waves and Applications*, 2:1, pp. 85-102, 1987.

3. A. Ishimaru and L. Tsang, "Backscattering enhancement of random discrete scatterers of moderate sizes," *Journal of the Optical Society of America A*, 5:2, pp. 228-236, February 1988.

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5. Y. Kuga, A. Ishimaru, and Q. Ma, "The second-order multiple scattering theory for the vector radiative transfer equation," *Radio Science*, 24:2, pp. 247-252, March-April 1989.

6. Y. Kuga and A. Ishimaru, "Backscattering enhancement by randomly distributed very large particles," *Applied Optics*, 28:11, pp. 2165-2169, June 1989.

7. A. Ishimaru, "Diffusion of light in turbid material," *Applied Optics*, 28:12, pp. 2210-2215, June 1989.

8. A. Ishimaru, "Experimental and theoretical studies on enhanced backscattering from scatterers and rough surfaces," in *Scattering in Volumes and Surfaces*, M. Nieto-Vesperinas and J. C. Dainty, editors, pp. 1-15. Amsterdam: Elsevier Science Publishers, 1990.

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11. Q. Ma, A. Ishimaru, P. Phu, and Y. Kuga, "Transmission, reflection, and depolarization of an optical wave for a single leaf," *IEEE Transactions on Geoscience and Remote Sensing*, 28:5, pp. 865-872, September 1990.

12. J. S. Chen and A. Ishimaru, "Numerical simulation of the second-order Kirchhoff approximation from very rough surfaces and a study of backscattering enhancement," *Journal of the Acoustical Society of America*, 88:4, pp. 1846-1850, October 1990.

13. A. Ishimaru and J. S. Chen, "Scattering from very rough surfaces based on the modified second-order Kirchhoff approximation with angular and propagation shadowing," *Journal of the Acoustical Society of America*, 88:4, pp. 1877-1883, October 1990.

14. A. Ishimaru, R. J. Marks II, L. Tsang, C. M. Lam, D. C. Park, and S. Kitamura, "Particle-size distribution determination using optical sensing and neural networks," *Optics Letters*, 15:21, pp. 1221-1223, October 1990.

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17. A. Ishimaru, "Wave propagation and scattering in random media and rough surfaces," *Proceedings of the IEEE*, 79:10, pp. 1359-1366, October 1991 (Invited Paper).

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19. Q. Ma and A. Ishimaru, "Propagation and depolarization of an arbitrarily polarized wave obliquely incident on a slab of random medium," *IEEE Transactions on Antennas and Propagation*, 39:11, pp. 1626-1632, November 1991.

20. K. Yoshitomi, A. Ishimaru, J.-N. Hwang, and J. S. Chen, "Surface roughness determination using spectral correlations of scattered intensities and artificial neural network technique," submitted to *IEEE Transactions on Antennas and Propagation*.

21. C. M. Lam and A. Ishimaru, "Calculation of Mueller matrices and polarization signatures for a slab of random medium using vector radiative transfer," submitted to *IEEE Transactions on Antennas and Propagation*.

22. C. M. Lam and A. Ishimaru, "Mueller matrix calculation for a slab of random medium with both random rough surfaces and discrete particles," submitted to *IEEE Transactions on Antennas and Propagation*.

23. P. Phu, A. Ishimaru, and Y. Kuga, "Controlled millimeter wave experiments and numerical simulations on the enhanced backscattering from one-dimensional very rough surfaces," submitted to *Radio Science*.

IV. PAPER PRESENTATIONS AT MEETINGS DURING THIS PERIOD

1. A. Ishimaru and Y. Kuga, "Experiment and Theory for Backscattering Enhancement and Imaging in Random Media," AGARD Electromagnetic Wave Propagation Panel Specialists' Meeting, Rome, Italy, May 1987.

2. Y. Kuga and A. Ishimaru, "Imaging of an Object Behind Randomly Distributed Spherical Particles Using Coherent Illumination," URSI Radio Science Meeting, Blacksburg, Virginia, June 1987.

3. Q. L. Ma, A. Ishimaru, and Y. Kuga, "Imaging of a Point Source Through a Slab of Random Scatterers Using the Diffusion Approximation," URSI Radio Science Meeting, Blacksburg, Virginia, June 1987.

4. S. L. Broschat, A. Ishimaru, and E. I. Thorsos, "The Phase Perturbation Technique vs an Exact Numerical Method for Random Rough Surface Scattering," URSI Radio Science Meeting, Blacksburg, Virginia, June 1987.

5. A. Ishimaru, "Theory and Application of Electromagnetic Scattering in Random Media," International Microwave Symposium, Rio de Janeiro, Brazil, July 1987 (Invited Paper).

6. Y. Kuga and A. Ishimaru, "Probability Density Function of the Observed EMI Field Due to Random Noise Sources," XXIInd General Assembly of URSI, Tel Aviv, Israel, September 1987.

7. A. Ishimaru, "Wave Propagation in Discrete Scatterers," XXIInd General Assembly of URSI, Tel Aviv, Israel, September 1987 (Invited Paper).

8. Y. Kuga and A. Ishimaru, "Backscattering Enhancement by Randomly Distributed Large Particles," National Radio Science Meeting, Boulder, Colorado, January 1988.

9. E. I. Thorsos and A. Ishimaru, "An Examination of the "Full-Wave" Method for Rough Surface Scattering," National Radio Science Meeting, Boulder, Colorado, January 1988.

10. A. Ishimaru, "Some New Developments in Wave Propagation and Scattering in Random Media," International Symposium on Radio Propagation, Chinese Institute of Electronics and URSI, Beijing, China, April 1988 (Invited Paper).

11. A. Ishimaru, Y. Kuga, and Q. Ma, "Experimental and Theoretical Studies of the Coherent Field, Scattering and Imaging in Random Media," International Symposium on Radio Propagation, Chinese Institute of Electronics and URSI, Beijing, China, April 1988 (Invited Paper).

12. Y. Kuga and A. Ishimaru, "Imaging of an Object Behind Randomly Distributed Particles," SPIE Technical Symposium Southeast, Orlando, Florida, April 1988.

13. Y. Kuga and A. Ishimaru, "Backscattering Enhancement by Randomly Distributed Particles of Different Sizes," SPIE Technical Symposium Southeast, Orlando, Florida, April 1988.

14. S. L. Broschat, E. I. Thorsos, and A. Ishimaru, "Rough Surface Scattering Using the Phase-Perturbation Technique," Acoustical Society of America Meeting, Seattle, Washington, May 1988.

15. M. J. Sierman, Y. Kuga, and A. Ishimaru, "Microwave Imaging Through Randomly Distributed Spherical Particles," URSI Radio Science Meeting, Syracuse, New York, June 1988.

16. A. Ishimaru, "Experimental and Theoretical Studies on Enhanced Backscattering from Scatterers and Rough Surfaces," International Workshop on Recent Progress in Surface and Volume Scattering, Madrid, Spain, September 1988 (Invited Paper).

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18. Q. Ma, Y. Kuga, and A. Ishimaru, "Solving an Electromagnetic Multiple Scattering Problem on the CRAY X-MP Supercomputer," NORTHCON Conference, Seattle, Washington, October 1988 (Invited Paper).

19. A. Ishimaru, "The Diffusion of Light in Turbid Material," 1988 Optical Society of America Annual Meeting, Santa Clara, California, October 1988 (Invited Paper).

20. A. Ishimaru, "First- and Second-Order Smoothing Method for Rough Surface Scattering," Acoustical Society of America Meeting, Honolulu, Hawaii, November 1988.

21. Y. Kuga and A. Ishimaru, "Backscattering Enhancement by Randomly Distributed Very Large Particles," National Radio Science Meeting, Boulder, Colorado, January 1989.

22. Y. Kuga, A. Ishimaru, and Q. Ma, "The Second-Order Multiple Scattering Theory for the Vector Radiative Transfer Equation," National Radio Science Meeting, Boulder, Colorado, January 1989.

23. A. Ishimaru, "Multiple Scattering Theories and Applications," National Institute of Standards and Technology," Boulder, Colorado, April 1989 (Invited Paper).

24. Q. Ma, A. Ishimaru, and P. Phu, "Propagation and Depolarization of an Arbitrarily Polarized Optical Wave Obliquely Incident on a Slab of Random Medium," URSI Radio Science Meeting, San Jose, California, June 1989.

25. Q. Ma, A. Ishimaru, and P. Phu, "Transmission, Bidirectional Reflectance and Depolarization of an Optical Wave for a Single Leaf," IGARSS'89/12th Canadian Symposium on Remote Sensing, Vancouver, British Columbia, Canada, July 1989.

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27. A. Ishimaru, "The Diagram Method for Rough Surface Scattering and A Study of Backscattering Enhancement," Progress in Electromagnetics Research Symposium, Massachusetts Institute of Technology, Cambridge, Massachusetts, July 1989.

28. Q. Ma, A. Ishimaru, and P. Phu, "Optical Scattering from Vegetation," Progress in Electromagnetics Research Symposium, Massachusetts Institute of Technology, Cambridge, Massachusetts, July 1989.

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31. A. Ishimaru, "Diffusion of Light in Tissues," 11th Annual International Conference of the IEEE Engineering in Medicine and Biology Society, Seattle, Washington, November 1989 (Invited Paper).

32. Y. Kuga, S. M. King, A. Ishimaru, and J.-S. Chen, "MMW Backscattering Enhancement by Very Rough One-Dimensional Surfaces," National Radio Science Meeting, Boulder, Colorado, January 1990.

33. Q. Ma and A. Ishimaru, "Propagation and Depolarization of an Arbitrarily Polarized Wave Obliquely Incident on a Slab of Random Medium," National Radio Science Meeting, Boulder, Colorado, January 1990. (2nd Place URSI Student Prize Paper Competition)

34. J.-S. Chen, S. M. King, P. Phu, A. Ishimaru, and Y. Kuga, "Numerical Simulation of Very Rough Surface Scattering and Comparison with Experiment," URSI Radio Science Meeting, Dallas, Texas, May 1990.

35. S.-H. Lou, L. Tsang, C.-H. Chan and A. Ishimaru, "Monte Carlo Simulations of Scattering of Waves by Random Rough Surface, Part I: Finite Element Method," URSI Radio Science Meeting, Dallas, Texas, May 1990.

36. C.-H. Chan, L. Tsang, S.-H. Lou, and A. Ishimaru, "Monte Carlo Simulations of Scattering of Waves by Random Rough Surface, Part II: Finite Difference Method," URSI Radio Science Meeting, Dallas, Texas, May 1990.

37. C.-M. Lam, D.-C. Park, L. Tsang, R. J. Marks, A. Ishimaru, and S. Kitamura, "Determination of Particle Size Distribution Using a Neural Network Trained with Backscatter Measurements," URSI Radio Science Meeting, Dallas, Texas, May 1990.

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39. A. Ishimaru, R. J. Marks, L. Tsang, C.-M. Lam, and D. C. Park, "Optical Sensing of Particle Size Distribution by Neural Network Technique," International Geoscience and Remote Sensing Symposium, University of Maryland, College Park, Maryland, May 1990.

40. Q Ma A. Ishimaru, and P. Phu, "A Combination Volume and Rough Surface Scattering Model for a Single Leaf," International Geoscience and Remote Sensing Symposium, University of Maryland, College Park, Maryland, May 1990.

41. A. Ishimaru, "Review of Scattering from Discrete Scatterers and Rough Surfaces," XXIIIrd General Assembly of URSI, Prague, Czechoslovakia, August 1990 (Invited Paper).

42. A. Ishimaru, "Experimental, Numerical and Analytical Studies of Scattering from Very Rough Surfaces and Backscattering Enhancement," International Workshop on Modern Analysis of Scattering Phenomena, Aix en Provence, France, s, 'ored by the European Research Office of the U.S. Army, London, United Kingdom, ..ptember 1990 (Invited Paper).

43. A. Ishimaru, "Modeling for Waves in Random Media - A Need for Analytical, Numerical and Experimental Investigations," International Conference on Directions in Electromagnetic Wave Modeling, New York, New York, sponsored by the Polytechnic Institute, October 1990 (Invited Paper).

44. A. Ishimaru and J. S. Chen, "Scattering from Very Rough Surfaces Based on the Modified Second-Order Kirchhoff Approximation with Angular and Propagation Shadowing," Acoustical Society of America Meeting, San Diego, California, November 1990.

45. A. Ishimaru, J. S. Chen, P. Phu, and K. Yoshitomi, "Backscattering Enhancement from Random Media and Rough Surfaces," North American Radio Science Meeting, The University of Western Ontario, London, Ontario, Canada, June 1991.

46. A. Ishimaru, P. Phu, C. M. Lam, and D. Fan, "Optical Scattering from Leaves and Soils," Progress in Electromagnetics Research Symposium (PIERS), Massachusetts Institute of Technology, Cambridge, Massachusetts, July 1991.

47. A. Ishimaru, J. S. Chen, P. Phu, and K. Yoshitomi, "Numerical, Analytical, and Experimental Studies of Scattering from Very Rough Surfaces and Backscattering Enhancement," Progress in Electromagnetics Research Symposium (PIERS), Massachusetts Institute of Technology, Cambridge, Massachusetts, July 1991.

48. S. H. Lou, L. Tsang, C. H. Chan, and A. Ishimaru, "Application of Finite Element Method to Monte Carlo Simulations of Scattering of Waves by Random Rough Surfaces: Penetrable Case," Progress in Electromagnetics Research Symposium (PIERS), Massachusetts Institute of Technology, Cambridge, Massachusetts, July 1991.

49. A. Ishimaru, J. S. Chen, P. Phu, and K. Yoshitomi, "Scattering from Very Rough Metallic and Dielectric Surfaces and Enhanced Backscattering," SPIE International Symposium on Optical and Optoelectronic Applied Science and Engineering, San Diego, California, July 1991.

50. A. Ishimaru, "Pulse Propagation in Random Media," SPIE International Symposium on Optical and Optoelectronic Applied Science and Engineering, San Diego, California, July 1991.

51. A. Ishimaru, "Diffusion of Light in Tissues," World Congress on Medical Physics and Biomedical Engineering, Kyoto, Japan, July 1991 (Invited Paper).

52. A. Ishimaru, "Backscattering Enhancement from Very Rough Surfaces and Random Media," International Commission for Optics Topical Meeting on Atmospheric, Volume, and Surface Scattering and Propagation, Florence, Italy, August 1991 (Invited Paper).

53. A. Ishimaru, "Backscattering Enhancement from Rough Surfaces," International Workshop on Light Propagation and Scattering in Dense Media and Rough Surfaces, University of Cantabria, Laredo, Spain, September 1991 (Invited Paper).

54. A. Ishimaru, "Optical Turbulence Effects on Propagation," SPIE International Symposium and Exhibition on Optical Engineering and Photonics in Aerospace Sensing, Orlando, Florida, April 1992 (Plenary Speaker).

55. A. Ishimaru, "Beam and Pulse Waves, Imaging and Enhanced Backscatter in Turbulence," SPIE International Symposium and Exhibition on Optical Engineering and Photonics in Aerospace Sensing, Orlando, Florida, April 1992 (Invited Paper).

56. A. Ishimaru, J.-N. Hwang, K. Yoshitomi, and J. S. Chen, "Remote Sensing of Rough Surface Parameters Using Artificial Neural Network Technique," International Geoscience and Remote Sensing Symposium (IGARSS '92), Houston, Texas, May 1992.

57. A. Ishimaru, "Leaky Surface Waves on Curved Surfaces," URSI Radio Science Meeting, University of Illinois, Chicago, Illinois, July 1992 (Invited Paper).

58. E. F. Fremouw and A. Ishimaru, "Enhanced Radar Cross Sections Due to Multiple Scattering in Turbulence," URSI Radio Science Meeting, University of Illinois, Chicago, Illinois, July 1992.

59. Y. Kuga, A. Ishimaru, and D. Rice, "Velocity of Electromagnetic Waves in Disordered Media," URSI Radio Science Meeting, University of Illinois, Chicago, Illinois, July 1992.

60. A. Ishimaru, J.-N. Hwang, K. Yoshitomi, and J. S. Chen, "Application of Artificial Neural Network (ANN) Technique to Rough Surface Inverse Scattering Problems," URSI Radio Science Meeting, University of Illinois, Chicago, Illinois, July 1992.

61. P. Phu, A. Ishimaru, and Y. Kuga, "Millimeter Wave Experiments on Backscattering Enhancement from One- and Two-Dimensional Very Rough Surfaces," URSI Radio Science Meeting, University of Illinois, Chicago, Illinois, July 1992.

62. C. M. Lam and A. Ishimaru, "Calculations of Mueller Matrices for Optical Waves Scattered from a Random Medium with Random Rough Surfaces and Discrete Particles," SPIE International Symposium on Optical Applied Science and Engineering, San Diego, California, July 1992 (Invited Paper).

63. A. Ishimaru, "Backscattering Enhancement in Random Media," URSI International Symposium on Electromagnetic Theory, Sydney, Australia, August 1992.

64. T. A. Seliga, A. Ishimaru, L. Tsang, Y. Kuga, C. H. Chan, P. Czapski, Z. Chen, and C. M. Lam, "Radar Polarimetry of Random Media," IEEE Second International Workshop on Radar Polarimetry, Nantes, France, September 1992.

65. A. Ishimaru, P. Phu, and Y. Kuga, "Controlled Millimeter Wave Experiments on the Enhanced Backscattering from Rough Surfaces," International Symposium on Antennas and Propagation, Sapporo, Japan, September 1992.

66. A. Ishimaru, C. M. Lam, and Y. Kuga, "Analysis of Mueller Matrices for Optical Waves Scattered from a Random Medium with Random Rough Surfaces and Discrete Particles," International Symposium on Antennas and Propagation, Sapporo, Japan, September 1992.

V. PARTICIPATING SCIENTIFIC PERSONNEL

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Controlled Millimeter Wave Experiments and Numerical Simulations on the Enhanced Backscattering from One–Dimensional Very Rough Surfaces

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ABSTRACT

We present experimental results on the scattering of electromagnetic waves at millimeter wave frequencies from one–dimensional very rough conducting surfaces with controlled surface roughness statistics. Very rough surfaces are defined as surfaces with rms height and correlation length on the order of a wavelength such that the rms slope is at least unity. It is expected that scattering experiments using these surfaces can provide useful insights since their statistics lie outside the range of validity of the present theories, namely, the Kirchhoff and perturbation theories. Strong backscattering enhancement at different incident angles, both in the TE and TM polarizations, are observed experimentally. Numerical calculations based on the exact integral equation method for cylindrical beamwave antennas compare favorably with the experimental results. The agreement between measurements and numerical calculations is good over a wide range of incident angles and for all scattering angles. The close agreement between the experimental results and numerical simulations indicates that this controlled experimental setup can be used to study scattering phenomena from one–dimensional very rough surfaces with different roughness statistics and from two–dimensional rough surfaces.

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Mueller Matrix Calculation For A Slab of Random Medium With Both Random Rough Surfaces And Discrete Particles

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Abstract

A model for a slab of random medium containing both random rough surfaces and discrete scatterers is presented in this paper. The refractive indices of the surrounding media are different from the background refractive index of the random medium. Kirchhoff rough surface theory is used to derive the transmittivity and reflectivity matrices for the scattering of electromagnetic waves from the rough surfaces. These matrices are used to determine a pair of boundary conditions for the vector radiative transfer equation. The multiple scattering due to the discrete scatterers is computed by solving the radiative transfer equation numerically including the rough surface scattering effect. Mueller matrices which characterize the random medium are constructed from the scattered Stokes vectors due to four independent polarized incident waves. The Mueller matrices are found to have symmetrical properties and there are eight nonvanishing matrix elements.

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CALCULATION OF MUELLER MATRICES AND POLARIZATION SIGNATURES FOR A SLAB OF RANDOM MEDIUM USING VECTOR RADIATIVE TRANSFER

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Abstract

The Mueller matrix which characterizes a slab of random medium containing spherical particles is calculated by using the vector radiative transfer theory. The vector radiative transfer equation is solved for arbitrarily polarized incident waves. The background refractive index of the slab is allowed to be different from the surrounding media. The scattering specific intensities for four independent polarized incident waves are calculated and used to construct the Mueller matrix. The Mueller matrix contains multiple scattering due to the randomly distributed particles governed by the vector radiative transfer theory. The calculated Mueller matrices are found to have symmetrical property and there are eight nonvanishing matrix elements. Polarization signatures are obtained at the backscattering direction from the Mueller matrix of the reflection side.

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SURFACE ROUGHNESS DETERMINATION USING SPECTRAL CORRELATIONS OF SCATTERED INTENSITIES AND ARTIFICIAL NEURAL NETWORK TECHNIQUE

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ABSTRACT

The artificial neural network (ANN) technique is applied to the determination of the rms height and the correlation distance of one-dimensional rough surfaces. The surface is illuminated by a beam wave, and the intensity correlations of the scattered wave at two wavelengths in the specular and backward directions are used to determine the roughness parameters. Scattered intensity correlations calculated by Monte Carlo simulations are used to train the ANN, and two methods, the explicit inversion method and the iterative constrained inversion method, are used to perform the inversion. The inversion values are compared with the target values, and the iterative constrained method is shown to give smaller errors, but requires longer computer CPU time.

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Propagation and Depolarization of an Arbitrarily Polarized Wave Obliquely Incident on a Slab of Random Medium

Qinglin Ma, *Member, IEEE*, and Akira Ishimaru, *Fellow, IEEE*

Abstract—The problem of how a slab of random medium affects the propagation and polarization of an arbitrarily polarized obliquely incident electromagnetic wave is investigated. The general formulation is given by using vector radiative transfer theory. The transfer equation with Stokes parameters is solved exactly by numerical methods and the multiple scattering solution is given in Fourier series. The multiple scattering solution is compared with the analytical first-order solution when the optical distance is small and the comparison shows that the results are consistent with each other. The multiple scattering results for a left-handed circularly polarized incident wave show that the transmitted wave is still left-handed polarized whereas the reflected wave becomes right-handed near the backscattering direction. A complete Mueller matrix can be established for any slab shaped random medium and the normalized scattering signature can be obtained by making use of the known Mueller matrix. The scattering signature obtained shows that for normal incidence we can obtain a maximum backscattered power if an arbitrarily oriented linearly polarized incident wave is chosen and that for an incident angle of 30°, we can get a minimum backscattered power if a linearly polarized incident wave is oriented at 45° or 135°.

Backscattering Enhancement: From Radar Cross Sections to Electron and Light Localizations to Rough Surface Scattering

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Abstract

Exciting new research is taking place in electromagnetics with results that are not predicted by conventional theories. Backscattering-enhancement phenomena are observed for radar cross sections, imaging, and for scattering from particles, rough surfaces, turbulence, and geophysical media. These phenomena have also attracted considerable attention among condensed-matter physicists, resulting in a large number of publications on wave localization in disordered media. This paper gives an historical development and an overview of the recent work on backscattering enhancement.

IEEE Antennas and Propagation Magazine, Vol. 33, No. 5, October 1991

Wave Propagation and Scattering in Random Media and Rough Surfaces

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Invited Paper

Many natural and man-made media such as the atmosphere, oceans, geophysical media, biological media, and composite and disordered materials have random spatial inhomogeneities and vary randomly in time, and these media are called "random media." Microwaves, optical waves, and acoustic waves propagating in these media experience random fluctuations in space and time, and these fluctuations affect a broad range of practical problems such as communications, remote-sensing, imaging, and object identification. In addition, waves in random media present one of the most challenging problems to theoreticians. This paper reviews the historical development, basic theories, and some recent new developments and discoveries, including backscattering enhancement.

Waves in Random Media 1 (1991) S91–S107. Printed in the UK

Numerical, analytical, and experimental studies of scattering from very rough surfaces and backscattering enhancement

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Abstract. This paper presents numerical simulations, theoretical analysis, and millimeter wave experiments for scattering from one-dimensional very rough surfaces. First, numerical simulations are used to investigate the effects of roughness spectrum, height variation, interface medium, polarization, and incident angle on the backscattering enhancement. The enhanced backscattering due to rough surface scattering is divided into two cases; the RMS height close to a wavelength and RMS slope close to unity, and RMS height much smaller than a wavelength with surface wave contributions. Results also show that the enhancement is sensitive to the roughness spectrum. Next, a theory based on the first- and second-order Kirchhoff approximation modified with angular and propagation shadowing is developed. The theoretical solutions provide a physical explanation of backscattering enhancement and agree well with the numerical results. In addition to the scattering of a monochromatic wave, the analytical results of the broadening and lateral spreading of a pulsed beam wave scattering from rough surfaces are also discussed. Finally, the existence of backscattering enhancement from one-dimensional very rough conducting surfaces with exact Gaussian statistics and Gaussian roughness spectrum is verified by a millimeter-wave experiment. Experimental results which show enhanced backscattering for both TE and TM polarizations for different angles of incidence are presented.

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Scattering from very rough metallic and dielectric surfaces: a theory based on the modified Kirchhoff approximation

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Abstract. This paper presents a theory of scattering from very rough metallic and dielectric surfaces using the first- and second-order Kirchhoff approximations (KA) modified with the angular and propagation shadowing. The shadowing functions limit the single and double scattered waves which are illuminated and not shadowed by the surface. The theoretical results are compared with the Monte Carlo simulations showing the range of validity of the theory. The theory is applicable to the range where the RMS height is close to a wavelength and the RMS slope is close to unity, and the second medium is lossy. The second-order scattering includes two waves travelling in opposite directions on the surface, giving a physical explanation of the enhanced backscattering.

Particle-size distribution determination using optical sensing and neural networks

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We present an inverse technique to determine particle-size distributions by training a layered perception neural network with optical backscattering measurements at three wavelengths. An advantage of this approach is that, even though the training may take a long time, once the neural network is trained the inverse problem of obtaining size distributions can be solved speedily and efficiently.

Scattering from very rough surfaces based on the modified second-order Kirchhoff approximation with angular and propagation shadowing

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A theory of scattering from very rough surfaces is presented. Both the surface rms height and the correlation distance are close to a wavelength and the rms slope is close to unity. The theory is based on the first-order and modified second-order Kirchhoff approximations. The second-order scattering includes the incident and scattering shadowing and the angular and propagation tapering shadowing. The angular shadowing limits the angular spectrum of the second-order scattering within those intercepted by the surface, while the propagation shadowing limits the propagation distance within those intercepted by the surface. The calculations are made for the rms height $\sigma/\lambda = 1.5$, 1.0, and 0.5 and the correlation distance $l/\lambda = 1.8$, and show close agreement with the Monte Carlo simulation of the exact integral equation. The results show that the first-order Kirchhoff scattering is dominant for $\sigma/\lambda = 0.5$, but for $\sigma/\lambda = 1.0$ and 1.5, the second-order scattering becomes comparable to the first-order and produces the enhanced backscattering. Therefore, this theory provides a possible physical explanation for the enhancement.

PACS numbers: 43.30.Gv, 43.30.Hw

Numerical simulation of the second-order Kirchhoff approximation from very rough surfaces and a study of backscattering enhancement

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A Monte Carlo simulation is used to study the second-order Kirchhoff scattering and backscattering enhancement of a scalar wave from one-dimensional soft Gaussian rough surfaces. The surfaces are very rough with the rms height $\sigma/\lambda = 0.707$, 0.5, and 0.3, and the correlation distance $l/\lambda = 1$. Numerical results of the scattered intensity using the Kirchhoff approximation and second-order scattering are compared with the exact calculations of the integral equation. With the corrections of incident and scattering shadowing and the propagation shadowing for the second-order scattering, good agreement between approximate and exact results is obtained. The results also show that the backscattering enhancement may be explained by the second-order Kirchhoff scattering including shadowing effects. The law of energy conservation and the problem of convergence in the simulation are also investigated. The results of numerical simulation may be useful for the development of an analytical model for very rough scattering.

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Transmission, Reflection, and Depolarization of an Optical Wave For a Single Leaf

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Abstract—Optical scattering by a single leaf is investigated, taking into account the structures inside a leaf and the leaf surface roughness. An optical scattering model, which includes both volume scattering and rough surface scattering, is developed using vector radiative transfer theory and Kirchhoff rough surface scattering theory. A leaf is modeled as a slab of water with an irregular surface containing randomly distributed spherical particles. The degree of polarization and the normalized scattering cross section per unit area for the transmitted and reflected copolarized and cross-polarized intensities are obtained for corn, potato, and laurel leaves. The theoretical results are compared with measured data to determine the parameters for the scatterers inside the leaf, the surface roughness, and the optical thickness. The agreement between the calculation and experiment for a wide variety of cases shows that this is a reasonable leaf model in the optical frequency regime.

Radio Science, Volume 25, Number 4, Pages 419–426, July–August 1990

Scattering and depolarization of waves incident upon a slab of random medium with refractive index different from that of the surrounding media

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The problem of how the difference of the refractive indices between the background medium and surrounding media affects the propagation of an electromagnetic wave is investigated in this paper. We present the general formulation for an arbitrarily polarized plane wave obliquely incident on a slab of random medium and compare the numerical multiple scattering solution of the integral-differential vector radiative transfer equation for latex particles with that of the analytical first-order scattering solution. The comparison shows good agreement between the two methods within the applicable range of the first-order approximation. From the cases studied we see that when the optical distance $\tau > 10$, the effects of the multiple-boundary reflection on wave propagation can be neglected for the calculation of the transmitted intensity but usually must be taken into account for the calculation of the reflected intensity and the degree of polarization.

Effect of a Random Medium on Microwave Imaging

MICHAEL J. SIERMAN, MEMBER, IEEE, YASUO KUGA, MEMBER, IEEE,
AND AKIRA ISHIMARU, FELLOW, IEEE

Abstract—**The effect of a random medium on the microwave imaging process is experimentally examined by positioning randomly distributed glass beads imbedded in thin styrofoam sheets in various densities between the target and the antennas. The main effect of the random medium is a reduction in the signal-to-noise (*S/N*) ratio for the tested medium with a small size parameter. If the medium consists of densely distributed particles, it is shown that the image quality is less than that of the sparsely distributed particle medium of the same optical distance.**

Scattering in Volumes and Surfaces
M. Nieto-Vesperinas and J.C. Dainty (Editors)

EXPERIMENTAL AND THEORETICAL STUDIES ON ENHANCED BACKSCATTERING FROM SCATTERERS AND ROUGH SURFACES

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This paper presents experimental and theoretical studies on the backscattering enhancement from discrete scatterers. The theory is based on the diffusion approximation and shows that the angular width of the peak is related to the transport length of the medium. The enhancement due to the rough surface scattering is divided into the case of large height variations and slopes and the case of small height variations with surface wave mode contributions.

1. INTRODUCTION

Backscattering enhancement phenomena have been observed for many years. It has been sometimes called the "retroreflectance" or the "opposition effect[1]." An example is "glory" which appears around the shadow of an airplane cast on a cloud underneath the airplane. The moon is brighter at full moon than at other times. Many materials such as $BaSO_4$ or $MgCO_3$ are known to cause the enhancement of scattered light in the backward direction. Some soils and vegetation are also observed to cause backscattering enhancement[2]. In spite of many observations, the several theories proposed to explain these phenomena are inadequate [1]. For example, the shadowing theory is based on the fact that in the scattering direction other than in the back direction, less light may be observed because of the shadowing. Also the scattering pattern of the surface or the scatterers such as Mie scattering may be often peaked in the back direction. The lens hypothesis is that the material may often act as corner reflectors or lenses resulting in peaked backscattering.

Recently, more quantitative experimental and theoretical studies of the enhancement have been reported. Watson[3] noted that the backscattered intensity is twice the multiple scattering and the first-order scattering. de Wolf[4] showed that the backscattered intensity from turbulence is proportional to the fourth-order moment and approximately twice the multiple scattered intensity. An excellent review is given by Kravtsov and Saichev[5]. Kuga and Ishimaru reported on an experiment which showed that the scattering from latex microspheres is enhanced in the backward direction with a sharp angular width of a fraction of a degree[6]. It was explained theoretically by Tsang and Ishimaru that the enhanced peak is caused by the constructive interference of two waves traversing through

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Diffusion of light in turbid material

Akira Ishimaru

This paper discusses some of the present knowledge of the mathematical techniques used to describe light diffusion in turbid material such as tissues. Attention will be paid to the usefulness and limitations of various techniques. First, we review the transport theory, radiance, radiant energy fluence rate, phase functions, boundary conditions, and measurement techniques. We then discuss the first-order solution, multiple scattering, diffusion approximation, and their limitations. The plane wave, spherical wave, beam wave, and pulse wave excitations are discussed followed by a brief review of the surface scattering effects due to rough interfaces.

I. Introduction

The scattering of light by turbid media has been studied extensively in the past,[1] and its applications include atmospheric optics, optics in the ocean, optical scattering in biological media, and scattering by stellar and interstellar media. In spite of these studies, however, the existing theoretical models are still not satisfactory for explaining the experimental data in many important and practical applications. This paper attempts to show some of the existing theoretical models and indicate their limitations and usefulness.

In turbid material, light is scattered and absorbed due to the inhomogeneities and absorption characteristics of the medium. A mathematical description of the propagation and scattering characteristics of light can be made in two different manners: analytical theory and transport theory.[1] In analytical theory, we start with Maxwell's equations, take into account the statistical nature of the medium, and consider the statistical moments of the wave. In principle, this is the most fundamental approach, including all diffraction effects, and many investigations have been made using this approach.[1-4] However, its drawback is the mathematical complexities involved, and its usefulness is limited.

Transport theory,[1] on the other hand, does not start with Maxwell's equations. It deals directly with the transport of power through turbid media. The development of the theory is heuristic and lacks the rigor of the analytical theory. Since both the analytical and transport theories deal with the same physical problem, there should be some relation between them. In fact, many attempts have been made to derive the transport theory from Maxwell's equations with varying degrees of success. In spite of its heuristic development, however, the transport theory has been used extensively, and experimental evidence shows that the transport theory is applicable to a large number of practical problems.[1]

We first review the transport theory and the first-order and multiple scattering theories. We then devote most of our discussion to the diffusion theory with its limitations and usefulness.

II. Transport Theory

The fundamental quantity in transport theory is the radiance $I(\mathbf{r},\hat{s})$, which is also called the specific intensity in radiative transfer theory and the brightness in radiometry. Its unit is W m^{-2} sr^{-1} Hz^{-1} and is the average power flux density in a given direction $\hat{s}$ within a unit solid angle within a unit frequency band (see Ref. 1, p. 149 for details). Since we normally use a laser source with a narrow bandwidth and a detector with sufficient bandwidth, we integrate over the frequency and redefine the radiance with the unit W m^{-2} sr^{-1}.

The fundamental differential equation for the radiance is the transport equation

$$\frac{d}{ds}I(\mathbf{r},\hat{s}) = -\gamma_t I(\mathbf{r},\hat{s}) + \frac{\gamma_t}{4\pi}\int p(\hat{s},\hat{s}')I(\mathbf{r},\hat{s}')d\omega', \tag{1}$$

where $\gamma_t = \gamma_s + \gamma_a$ is the extinction coefficient in m^{-1}, γ_s is the scattering coefficient, γ_a is the absorption coefficient, $p(\hat{s},\hat{s}')$ is the phase function, and $d\omega'$ is the elementary solid angle about the direction $\hat{s}'$.

The quantity most useful in light diffusion in tissue is called the radiant energy fluence rate and is denoted

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Backscattering enhancement by randomly distributed very large particles

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Recently, the backscattering enhancement by densely distributed particles of a size comparable to the wavelength was reported. It has been explained as the constructive interference of two waves traveling in opposite directions. This enhancement was observed only in densely distributed particles, and its existence in sparsely distributed media has not been verified yet. In this paper we present the experimental evidence of backscattering enhancement by sparsely distributed very large particles. Experiments are conducted using 45-μm latex particles which are approximately 100 times the wavelength. Both copolarized and cross-polarized components are measured for different particle concentrations. Unlike for small particles, backscattering enhancement is most noticeable when the particle concentration is low. The angular width of the peak is comparable to the ratio (wavelength)/(particle size) and is independent of the optical distance.

I. Introduction

Backscattering enhancement by random media is important in many areas including remote sensing and solid state physics. The experimental evidence of backscattering enhancement by randomly distributed particles was first reported by Kuga and Ishimaru and later by other groups.[1–4] This enhancement is caused by the constructive interference of two waves traveling through identical multiple scattering paths in opposite directions.[5,6] It is also known as the weak Anderson localization effect in solid state physics. We call this backscattering enhancement type I. The backscattering enhancement is strongly influenced by size parameter ka ($ka = 2\pi a/\lambda$), where λ is the wavelength and a is the radius of particles.[7]

The characteristics of enhancement type I are as follows: (1) it is most visible when the particle sizes are comparable to the wavelength $1 < ka < 20$, (2) the peak is observable only in densely distributed particles, (3) the maximum enhancement is 3 dB compared to the nonenhanced intensity, (4) the angular width of the peak is <0.1–0.2°, (5) the angular width and the amount of enhancement are related to the transport optical distance $\tau_{tr} = \rho\sigma_t L(1 - \bar{\mu})$, where ρ is the number density, σ_t is the scattering cross section, L is the path length, and $\bar{\mu}$ is the average cosine, and (6) the enhancement is most visible when τ_{tr} is large. When the particle sizes become much larger than the wavelength, it is believed that backscattering enhancement type I is not observable.[7]

Backscattering enhancement can also be caused by large particles and turbulence. This type of enhancement is known as the focusing effect.[8,9] We call this backscattering enhancement type II. Because type II enhancement is caused by the focusing effect, the intensity enhancement is related to the particle size or the turbulence scale size, and the enhancement can be much more than 3 dB.

In this paper we show the experimental evidence of type I backscattering enhancement by sparsely distributed large particles. Unlike for small particles, the backscattering enhancement by large particles is most noticeable when the particle concentration is low. The angular width of the peak is comparable to the ratio (wavelength)/(particle size) and is independent of the optical distance.

II. Experiments

The experimental setup is shown in Fig. 1. A He–Ne laser with an expanded beam diameter of 30 mm is used as the light source. The incident wave is vertically (out of the paper) polarized. The detector, which consists of a polarizer, a 5-mm input aperture, a lens, and a 50-μm pinhole, has a field of view (FOV) of 0.09° and is mounted on the computer-controlled rotational stage. The light output of the optical fiber cable is focused on a temperature-controlled photomultiplier.

Uniform latex microspheres manufactured by Dow Chemical are used as scatterers. The mean diameter and the standard deviation are 45 and 9.9 μm, respec-

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The second-order multiple scattering theory for the vector radiative transfer equation

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Vector radiative transfer (RT) and first-order multiple scattering (FOMS) theories are often used for analyzing the depolarization effect by the random medium. However, the numerical solution for the RT theory is limited to moderate-sized particles because of the numerical stability. In order to analyze the depolarization effect by large particles near the backscattering direction, we obtained the second-order multiple scattering (SOMS) theory for the vector RT theory. The derivation was based on the second-order solution of each Fourier component of the Stokes vector. The numerical results were compared with FOMS and RT theories. It was shown that the SOMS theory was most useful for large particles and near the backscattering direction. Experimental results for large spherical particles were compared with the SOMS theory. The second-order ladder term which was included in the SOMS theory was not sufficient to explain the sharp peak observed in the backscattering direction in the depolarized intensity. The peak appears to be caused by the backscattering enhancement effect.

IMAGING OF AN OBJECT BEHIND RANDOMLY DISTRIBUTED PARTICLES USING COHERENT ILLUMINATION

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ABSTRACT

We present experimental studies of the imaging of an object behind randomly distributed spherical particles using coherent illumination. The object, which has black stripes on white diffuse paper with different spatial wavelengths, is placed behind a scattering cell and illuminated by an expanded HeNe laser beam. Results are obtained for different particle sizes and optical distances. The differences between the front and back illumination are studied. The diffucion approximation is used to calculate the modulation transfer function for the front illumination.

1. INTRODUCTION

Image transmission through random media has been studied extensively in recent years. The quality of images transmitted through a random medium is usually expressed by the modulation transfer function (MTF). This is a ratio of the modulation in the image to that in the object as a function of the spatial frequency (cycles/mm or cycles/radian). There are two types of imaging system: passive and active. In the passive imaging system the object is the incoherent source and the scattered light is detected through the random media. We have studied passive imaging through randomly distributed particles [1]. We obtained excellent agreement between experimental results and theory using the small-angle approximation for the radiative transfer theory [2]. We have also studied the effective range of the small-angle approximation by comparing it with the radiative transfer theory [5].

In an active imaging system in which an object behind a random medium is illuminated by a coherent wave, the incident wave of an object is not only the reduced coherent wave but also the incoherent scattered wave, and the reflected wave from the object must go through a random medium before reaching the detector. In this paper we present experimental studies of the imaging of an object behind randomly distributed spherical particles using coherent illumination.

2. EXPERIMENTS

The experimental setup is shown in Fig. 1. The object, which had black stripes on white diffuse paper with different spatial wavelengths, was placed behind a scattering cell and illuminated by an expanded HeNe laser beam from the front side. The image-forming optics consisted of an iris diaphragm (aperture diameter, 5 mm) and a lens with a focal length $f_0 = 50$ mm and thickness $t = 4.5$ mm. Since the lens thickness was much less than the focal length, the thin-lens formula was applied. The length from the lens to the detector (d) and the equivalent air length from the object to the lens (L) were 68.5 and 185 mm, respectively. Because a water-filter spectrophotometer cell (SC) was used, the actual length between the object and the lens was longer than the equivalent air length (192 mm compared with 185 mm). The distances L and d satisfied the following lens formula.

$$\frac{1}{L} + \frac{1}{d} = \frac{1}{f_o}, \tag{1}$$

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Backscattering enhancement of random discrete scatters of moderate sizes

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The scattering of waves by particles of moderate size is nonisotropic. In this paper, the backscattering enhancement of scattering of waves by nonisotropic scatterers is studied. Multiple-scattering effects are included by examining the summation of all the ladder terms and all the cyclical terms. It is shown that if the observation angle is in the neighborhood of the backscattering direction, then both summations can be related to the unidirectional point-source Green's function of the transport equation. For the case of small albedo or small optical thickness, the second-order theory is applied to calculate the Green's function. The angular width of backscattering enhancement in this case is of the order of the coherent wave attenuation rate divided by the wave number. For the case of a large albedo and a large optical thickness, the diffusion approximation is used to calculate the Green's function. For this case, the angular width is of the order of the transport rate divided by the wave number. The transport rate is equal to the product of the coherent wave-attenuation rate and 1 minus the mean cosine of the scattering angle. Hence the predicted angular width is substantially smaller for particles with dominant forward scattering and is shown to be in good agreement with experimental observations.

Journal of Electromagnetic Waves and Applications. Vol. 2. No. 1. 85–102. 1987

A Numerical Comparison of the Phase Perturbation Technique with the Classical Field Perturbation and Kirchhoff Approximations for Random Rough Surface Scattering

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Abstract– The classical field perturbation and Kirchhoff approximations can be viewed as low and high frequency solutions to the rough surface scattering problem. The former is accurate for surfaces whose roughness is much smaller than the wavelength of the incident field and the latter for surfaces that have large radii of curvature relative to the incident wavelength. However, there is a need for a solution that applies to surfaces rough on scales comparable to the incident wavelength. Ideally this solution must also reduce to the two classical solutions in the appropriate limits. In this paper we examine the recently-developed phase perturbation technique. We show numerically that for a one-dimensional surface with Gaussian roughness spectrum satisfying Dirichlet boundary conditions the phase perturbation reflection coefficient reduces to that of field perturbation theory for small surface roughness and to that of the Kirchhoff approximation for gently undulating surfaces. It is also numerically shown that the phase perturbation backscattering coefficient reduces to those of first-order field perturbation theory and the Kirchhoff approximation in the appropriate limits.

INTRODUCTION

Many engineering and scientific problems arise which require a thorough understanding of wave scattering from rough surfaces. For example, knowledge of rough surface scattering is important in areas such as remote sensing, integrated optics, radio communications, oceanography, radio astronomy, surface profilometry, underwater acoustics, and surface physics [1–4].

BEAM WAVE PROPAGATION AND SCATTERING IN RANDOM MEDIA BASED ON THE RADIATIVE TRANSFER THEORY

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ABSTRACT

Many studies have been conducted on beam wave propagation in turbulent media where the scattered waves are confined within small forward angles. However, the beam wave in randomly distributed particles can be scattered in wider angles, and the parabolic equation technique cannot be used in most cases. This paper presents a numerical solution of beam wave propagation based on the radiative transfer theory. The incident wave is assumed to be a monochromatic, unpolarized, collimated beam with a finite beam width. The Fourier-Bessel transform is used to obtain the equation of transfer for each spatial frequency, and the numerical solution is obtained using two-dimensional Gauss quadrature and an eigenvalue-eigenvector technique. Numerical solutions are given for transmitted and backscattered specific itensities and transmitted power for various optical depths, mean cosine of the phase function, and beam sizes, showing the effectiveness of the method.